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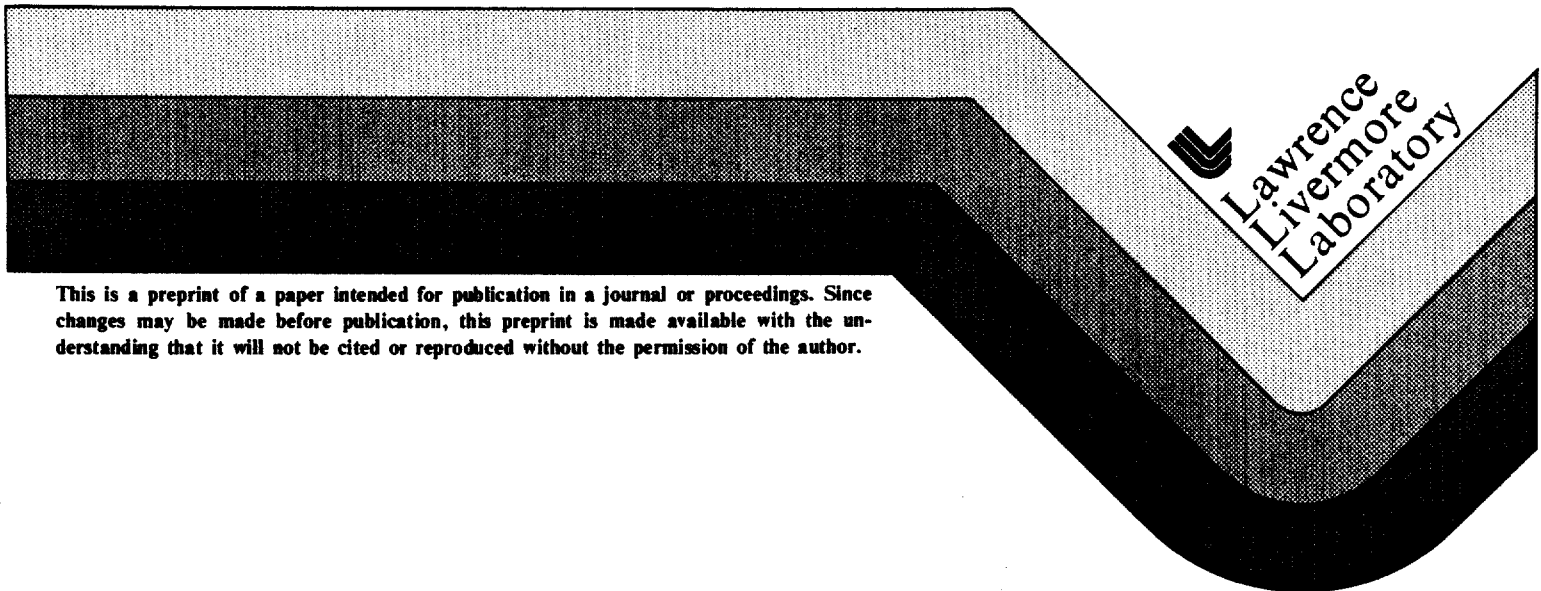
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ELASTIC-PLASTIC, AND FULLY PLASTIC FAILURE
MODELS IN THE ASSESSMENT OF PIPING INTEGRITY

R. D. Streit
Lawrence Livermore National Laboratory
Livermore, California 94550

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COMPARISON OF LINEAR-ELASTIC-PLASTIC, ELASTIC-PLASTIC, AND FULLY PLASTIC FAILURE MODELS IN THE ASSESSMENT OF PIPING INTEGRITY

R. D. STREIT

Lawrence Livermore National Laboratory
Livermore, California 94550

SUMMARY

The failure evaluation of Pressurized Water Reactor (PWR) primary coolant loop pipe is often based on a plastic limit load criterion; i.e., failure occurs when the stress on the pipe section exceeds the material flow stress. However, in addition the piping system must be safe against crack propagation at stresses less than those leading to plastic instability. In this paper, elastic, elastic-plastic, and fully-plastic failure models are evaluated, and the requirements for piping integrity based on these models are compared. The model yielding the "more" critical criteria for the given geometry and loading conditions defines the appropriate failure criterion.

The pipe geometry and loading used in this study was chosen based on an evaluation of a guillotine break in a PWR primary coolant loop. It is assumed that the piping may contain cracks. Since a deep circumferential crack, can lead to a guillotine pipe break without prior leaking and thus without warning it is the focus of the failure model comparison study. The hot leg pipe, a 29 in. I.D. by 2.5 in. wall thickness stainless pipe, was modeled in this investigation. Cracks up to 90% through the wall were considered.

The loads considered in this evaluation result from the internal pressure, dead weight, and seismic stresses. For the case considered, the internal pressure contributes the most to the failure loading. The maximum moment stress due to the dead weight and seismic moments are simply added to the pressure stress. Thus, with the circumferential crack geometry and uniform pressure stress, the problem is axisymmetric. It is analyzed using NIKE2D--an implicit, finite deformation, finite element code for analyzing two-dimensional elastic-plastic problems.

Elastic, elastic-plastic and fully-plastic models are considered. Although the pipe material is very tough, linear-elastic fracture concepts are employed to establish a lower bound fracture criteria and to check the validity of the elastic-plastic solutions at low loads where elasticity dominates. The J-integral is employed in the elastic-plastic fracture analysis. J is calculated from the change in system potential energy as a function crack extension for loads leading to net section plastic instability. The onset of crack growth will corresponds to either J reaching J_{IC} or the average stress in the remaining ligament of the cracked section reaching the material flow stress. Here the flow stress is defined as the average of the yield and ultimate strength. The criteria which is reached first will govern fracture. For the hot leg pipe under consideration we found that exceeding the material flow stress on the remaining ligament is the more critical criteria. As the flow stress was reached, J would increase rapidly, however J remained below J_{IC} for all loads up to the critical stress criterion.

1. Introduction*

A double-ended guillotine break in the primary coolant loop of a pressurized water reactor (PWR) is a postulated loss of coolant accident which can result in extreme dynamic loads (i.e., the asymmetric blowdown load) on the reactor pressure vessel (RPV) and vessel internals. Design and construction of the RPV and support systems to withstand these extreme dynamic loads is very difficult. Similar high loading would also be experienced in a boiling water reactor given a similar accident. Although such a break would be an extremely rare event, its obvious safety and design implications demand that it is carefully evaluated.

The United States Nuclear Regulatory Commission (USNRC) and industry have devoted considerable time and effort to evaluating piping integrity. While various failure criteria have been developed and applied to different piping systems, only that criterion yielding the most critical design requirement (i.e., lowest applied loading) is appropriate to the prediction of piping failure. Thus, for different pipes and piping systems the critical failure criteria can vary depending on the material, loading, and pipe and system geometry. Further, when piping reliability is evaluated during plant life the possibility of damaged or flawed pipes must also be considered.

The work discussed here is part of the Load Combinations Program at Lawrence Livermore National Laboratory to estimate the probability of a double-ended guillotine break in the primary reactor coolant loop of a selected PWR. The program employs a fracture mechanics based fatigue model to propagate cracks from an initial flaw distribution. It was found that while most of the large cracks grew into leaks, a complete (or nearly complete) circumferential crack could lead to a double-ended pipe break with prior leaking and thus, without warning. It is important to assess under what loads such a crack will result in complete pipe severance. The loads considered in this evaluation result from pressure, dead weight and seismic stresses. For the PWR hot leg considered in this investigation the internal pressure contributes the most to the load controlled stresses (i.e.; stresses which can cause piping failure) and thus, the problem is treated as axisymmetric with uniform axial loading.

Evaluation of the critical loading requires an appropriate failure criteria. Due to the large deformation characteristic of reactor piping material this evaluation has often been based on plastic limit load considerations, that is exceeding the material flow stress in a pipe section (flawed or unflawed). However, in addition the piping system must be safe against crack propagation. Thus, the complete range of failure criterion - i.e., linear-elastic, elastic-plastic, and fully plastic - must be considered. In this investigation we consider the fracture of a 316 stainless steel pipe representative of a typical PWR hot leg. The pipe has a 29 in. (73.7 cm) I.D. with a wall thickness of 2.5 in. (6.35 cm).

2. Pipe Failure Models

Linear-elastic, elastic-plastic, and fully plastic failure models were evaluated. The elastic model employs linear-elastic fracture mechanics. For this case, the stress intensity for the circumferential crack geometry (at various crack lengths) is compared to K_{IC} at a load sufficient to cause yielding in

*This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

the remaining ligament, Figure 1. On the left hand side of Fig. 1 the stress intensity is made non-dimensional with respect to the stress applied away from the cracked section. For a stress equal to the material yield strength of 30 ksi (207 MPa) applied to the uncracked pipe section we find that K_I approaches K_{IC} (300 ksi-in^{1/2}, 330 MPa-m^{1/2}) only for very long cracks. Under these conditions the stress on the remaining ligament of the cracked section is many times the material flow stress and thus failure is due to an elastic-plastic or fully plastic criteria. The right side of Fig. 1 shows the non-dimensional stress-intensity for the condition that the stress in the remaining ligament equals a constant, i.e. the flow stress. We observe that cracks 40-60 percent through the pipe wall actually give the highest relative stress intensity. However, even in this regime the stress intensity is many times less than K_{IC} . The rapid decrease in the non-dimensional stress intensity beyond .6(a/h) reflects the large reduction in crack area relative to the uncracked section. Thus, due to the high toughness of 316 stainless steel, linear elastic fracture mechanics is not applicable to the pipe fracture problem considered here.

The J-integral is used to extend the linear-elastic fracture concepts into the elastic-plastic regime. This analysis employs the potential energy definition of the J - integral [1];

$$J = -\frac{\partial U}{\partial A}$$

$$= \int_0^P \frac{\partial \Delta(\bar{P}, a)}{\partial a} d\bar{P}$$

where U is the potential energy in a cracked body and A is the crack area, Figure 2. By evaluating the load-deflection behavior of two similar pipe lengths with circumferential cracks of depth (a and a + Δa) we can estimate J as a function of load. Crack initiation will occur when J exceeds J_{IC} , i.e. greater than 3000 in-lb/in² (525 kJ/m²). J is compared to the stress in the remaining ligament for loads up to and exceeding extensive flow in the cracked section.

For the fully plastic analysis, the plastic limit load is reached when the nominal stress in the remaining ligament, σ_{RL} , equals the material flow stress, σ_0 . In this study the flow stress is defined as the average of the .2 percent offset yield and ultimate strength. This definition accounts for work hardening and has been found useful for limit load calculations. [2] We have also found that this correlates well with gross deformation in the crack vicinity. Based on available data, the flow stress for 316 stainless steel is 50 ksi (345 MPa).

The critical fracture initiation criteria is assessed by comparing the value of the J-integral to J_{IC} when the stress in the remaining ligament equals σ_0 . A crack tearing model^[3] would normally be employed to evaluate crack stability after crack initiation, however, in this study J_{IC} proved to be adequately high. The J and material flow models require elastic-plastic material behavior. A true stress-strain relation for the 316 stainless was developed using standard 0.25 in (0.635 cm) diameter tensile specimens. The cross-sectional area of the specimen (and inturn strain) was monitored as a function of load and subsequently converted into the desired true stress and strain. This elastic-plastic relation was then employed in the analysis model as will be discussed.

3. Analysis and Discussion

The pipe analyzed in this study has a 29 in. (73.7 cm) ID with a wall thickness of 2.5 in. (6.35 cm) as discussed earlier. A pipe length of 30 in (76.2 cm) was used in the analysis so as to ensure that the moment induced by the crack had damped to a small fraction of its initial value. Three different finite element zonings of the pipe were used in the analysis - for short, intermediate and long cracks. In this way the elements sizes in the vicinity of the crack were kept small, whereas wasted elements could be avoided away from the crack without having to rezone for each new crack length. The problem is treated as axisymmetric with uniform axial loading as discussed earlier.

Stress and displacement fields for the J-integral evaluation were calculated using NIKE2D - an implicit finite deformation, finite element code for analyzing two-dimensional elastic-plastic problems.^[4] Pipe displacement, as a function of applied load, is tabulated for crack length pairs, a_m and a_{m+1} , and J calculated using an incremental form of eq. 1, as shown in eq. 2;

$$J_i = \frac{1}{2\pi r(a_{m+1} - a_m)} \sum_1^i \Delta P \left[\frac{(\delta_{i+1,m+1} + \delta_{i,m+1})}{2} - \frac{(\delta_{i+1,m} + \delta_{i,m})}{2} \right] \quad (2)$$

Here, J_i is the J value at the i th load level and $\delta_{i,m}$ is the pipe displacement at the i th load level with a crack length of a_m (see Fig. 2). A plot of J versus the applied axial stress is shown in Fig. 3.

In Fig. 4 J is plotted as a function of the average stress in the remaining ligament of the pipe for various crack depths. For average stresses less than yield in the remaining ligament the J values remain very low - i.e., less than 5% of J_{IC} . However, as the average stress in the remaining ligament approaches σ_0 , J increases very rapidly. This result is to be expected since the increased plasticity will result in relatively large crack openings and inturn large J-integral values. In all cases however, the critical flow stress was reached prior to J exceeding the crack initiation J_{IC} value. Thus, plastic flow in the remaining ligament is the critical failure criteria.

It is also interesting to note that the intermediate length cracks ($.4 \leq a/h \leq .6$) come the closest to reaching the J-integral controlled fracture criteria. As the crack length is further increased, the decrease in the remaining area (used to calculate stress in the remaining ligament) outweighs the increase in crack length (which is important to the J-integral evaluation). This is also true for the linear elastic case as discussed with reference to Fig. 1.

The effect of plasticity is observed when $(J)^{1/2}$ is plotted versus the applied stress. Using LEFM we would expect a linear relation between load and $J^{1/2}$ (i.e., $J_{LEFM} = K^2/E$). This linear relation is confirmed for low loads when the plastic deformation is confined to a few elements in the vicinity of the crack tip, Fig. 5. However, as the load, and in turn the plasticity in the vicinity of the crack is increased, deviations from linearity are experienced. In this regime the LEFM solution acts as a lower bound estimate of J ; i.e., J_i (elastic-plastic) $\geq J_i$ (linear-elastic). The crack opening resulting from plastic deformation will be larger than that due to purely linear-elastic behavior. Since J is proportional to crack opening displacement, we would expect the observed behavior.

A perfectly plastic estimate of J and tearing* was also calculated following the work of Paris, Tada and Gamble^[5]. This was used to establish an upper bound estimate on J and estimate the tearing for the reactor coolant loop under consideration. Although J values calculated in this way were often a few times J_{IC} , the tearing slope was considerably less than estimates of the material tearing resistance. Thus, using this perfectly plastic model we would conclude that if a crack of sufficient size were present, to initiate crack growth, it would be stable and thus the crack would arrest.

4. Conclusions

Three failure models (linear-elastic fracture, elastic-plastic J-integral, and net-section plastic instability) have been compared to predict the critical criteria for the fracture of a 29 in. (73.7 cm) ID, by 2.5 in. (6.35 cm) thick 316 stainless steel pipe. For the PWR hot leg under uniform axial loading the critical failure criteria is the net-section plastic instability; i.e, when the average stress on the remaining ligament exceeds the material flow stress.

The potential energy definition of the J-integral was used to estimate J as a function of load for the elastic-plastic analysis. A linear elastic analysis of J , i.e., the stress intensity solution (in terms of J), provided a lower bound estimate of J , whereas, a plastic limit load analysis gave an upper bound value. The results are self consistent and appear realistic when compared to observed behavior.

*The tearing is proportional to the slope of the J versus crack extension curve. It provides a useful means of assessing crack growth stability after crack growth initiation.

5. References

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6. Figure Captions

- Fig. 1 Linear elastic stress intensity as a function of crack depth for a complete internal circumferential crack in a pipe with $r/h = 5$ loaded by a uniform axial load. On the left the stress intensity is made non-dimensional with the applied load and pipe thickness. The right side shows the non-dimensional stress intensity for an applied load giving a stress on the remaining ligament equal to the material flow stress, σ_0 .
- Fig. 2 Schematic representation of the procedure used in the potential energy calculation of the J-integral.
- Fig. 3 J for a complete internal crack (depth a) in a pipe as a function of the applied nominal stress. The pipe material is 316 stainless steel with an I.D. of 29 in. (73.7 cm) and a wall thickness $L = 2.5$ in. (6.35 cm).
- Fig. 4 J for a complete internal circumferential crack (depth a) in a pipe as a function of the average stress on the remaining ligament. Note that for all cracks the curves cross into the region of failure by net section plastic flow prior to reaching the critical elastic-plastic fracture criteria. The pipe is 316 stainless steel with an I.D. of 29 in. (73.7 cm) and a wall thickness of 2.5 in. (6.35 cm).
- Fig. 5 Relation between $J^{1/2}$ and the applied nominal stress for a 316 stainless steel pipe with I.D. = 29 in. (73.7 cm) and a wall thickness of 2.5 in. (6.35 cm). For low loads and relatively short cracks the curves are linear as predicted by linear elastic fracture mechanics.

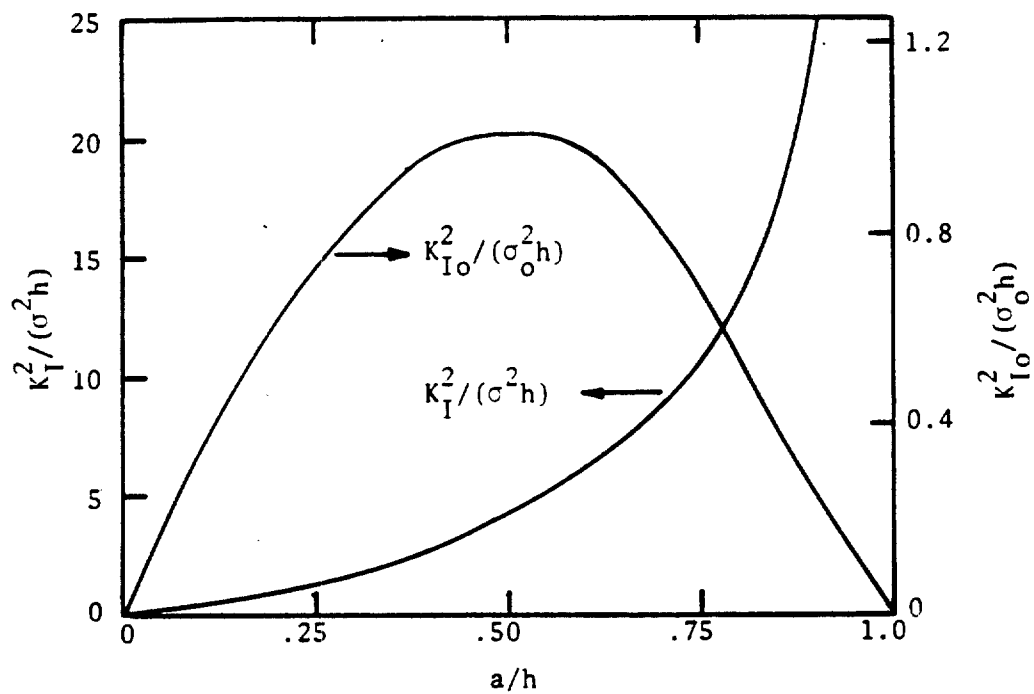


FIGURE 1

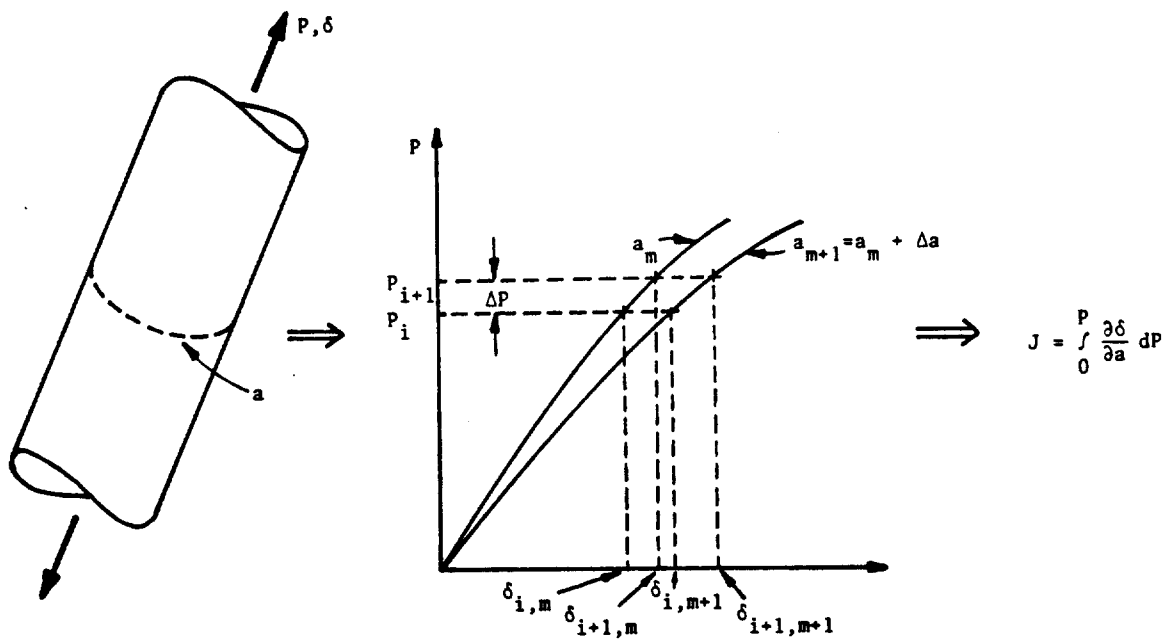


FIGURE 2

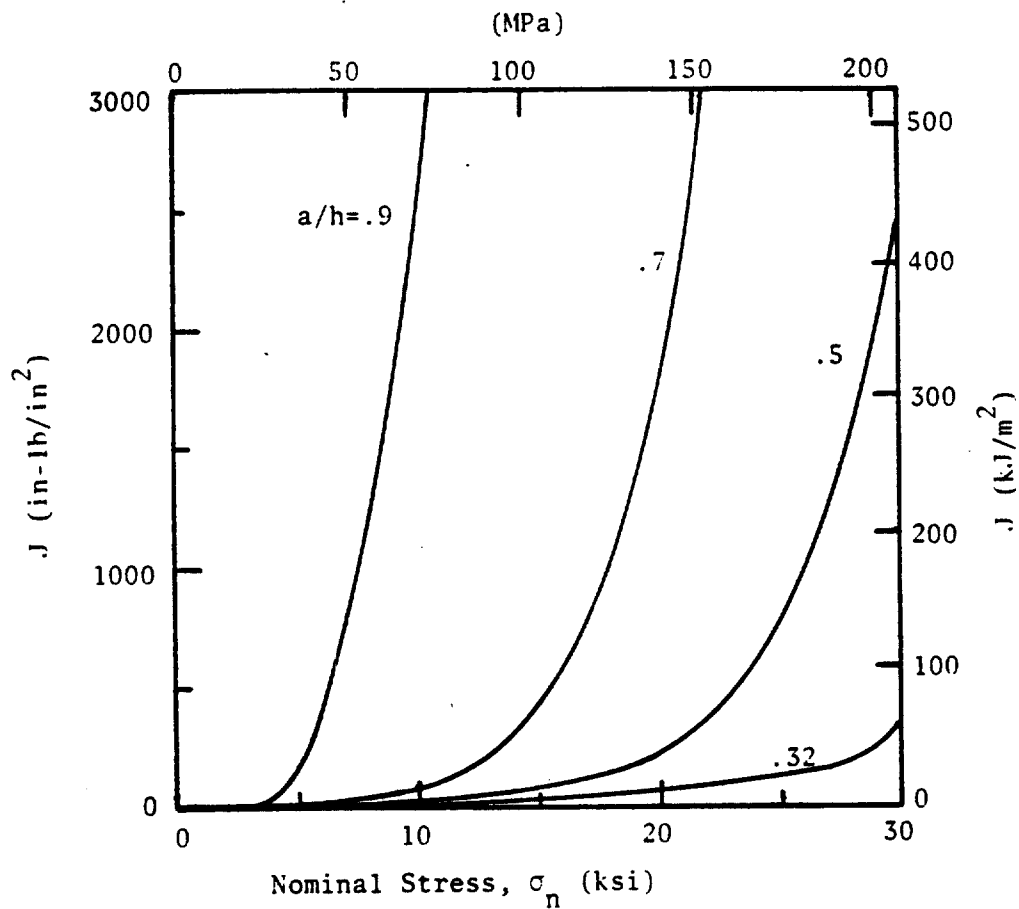


FIGURE 3

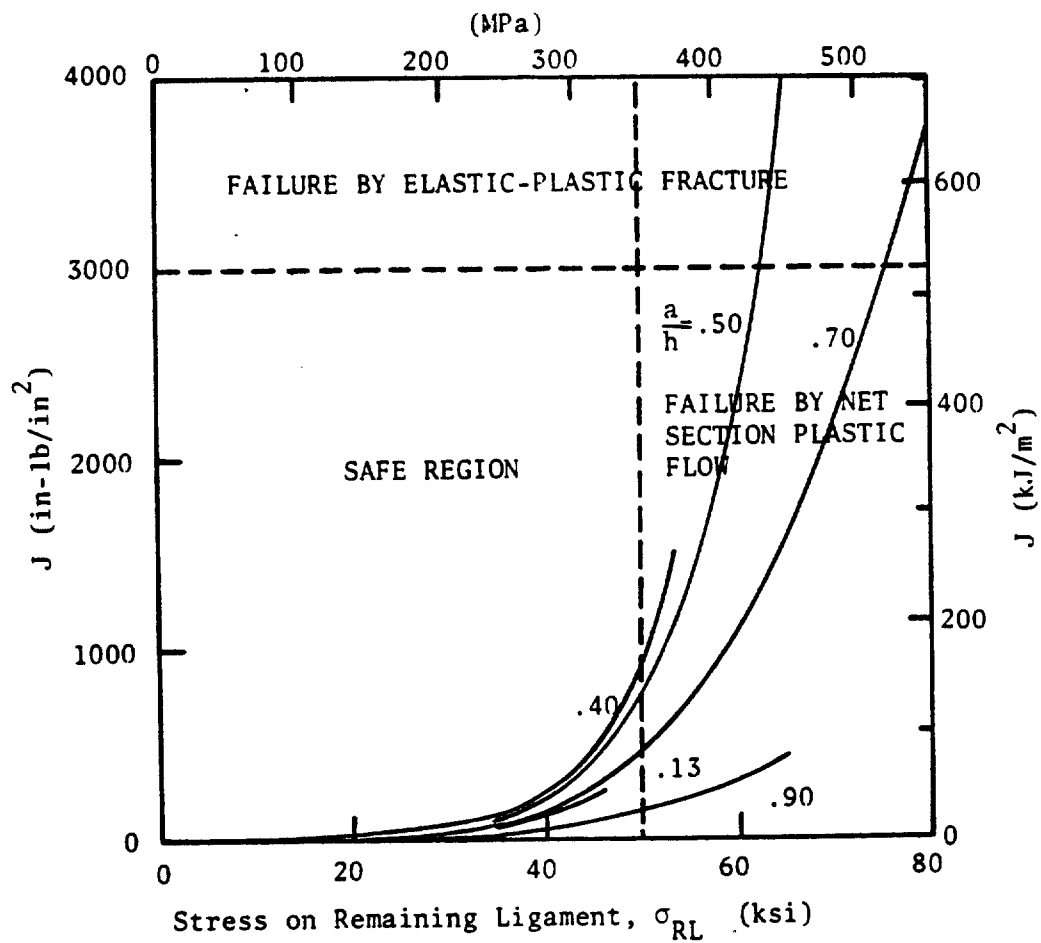


FIGURE 4

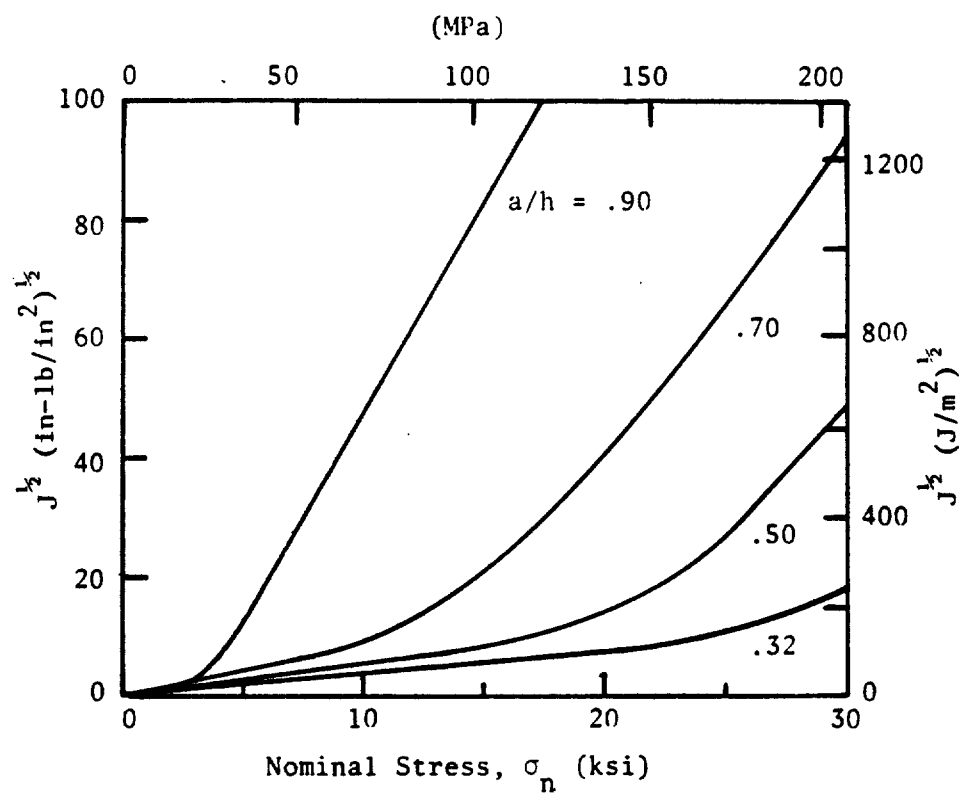


FIGURE 5